Perceived Instability and Co-Contraction in Patients Undergoing Total Knee Arthroplasty

Undergraduate Honors Thesis

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By

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Abstract

Osteoarthritis (OA) is a disease characterized by the breakdown of cartilage in a joint. It is most common in the knee joint, with 14 million Americans experiencing knee OA in the United States alone. Patients with knee OA often report pain, stiffness, and instability that affects their daily lives. These patients often utilize an involuntary muscle activation strategy in their lower extremity known as co-contraction, in which agonist and antagonist muscles activate simultaneously. This strategy may increase the perception of stability in the knee, but it also increases the load on the joint.

Total knee arthroplasty (TKA) is the most common treatment for advanced knee OA, with over 600,000 primary TKAs performed in the United States each year. While TKA has been proven to decrease pain, increase knee range-of-motion, and improve patient function, many patients still exhibit elevated co-contraction levels and report instability after surgery. This instability may be due to insufficient support from passive and active stabilizers in the knee. To improve patients' TKA outcomes, it is important to relate measurable variables before, during, and after surgery to post-operative measures of function. The purpose of this research is to understand how co-contraction is related to patient function, and to determine how the perception of instability is related to surgical technique and other variables before and after surgery.

Forty-three patients awaiting TKA provided IRB-approved written consent as part of larger project in the Neuromuscular Biomechanics Lab. Data were collected on each patient's kinematics and muscle activation patterns during gait, as well as each patient's strength, perception of instability, and function before, 6 months after, and 2 years after TKA. Function was measured by performance on clinical tests (Six Minute Walk Test, Stair-Climbing Test, Timed Up-and-Go Test) and by patients' responses to clinically-administered surveys (Knee

Injury and Osteoarthritis Outcome Score, Short-Form Health Survey). During surgery, the orthopaedic surgeon measured passive knee laxity and balance using custom instrumentation. These measurements were used as a metric for surgical technique.

Greater perceived instability was related to higher co-contraction and weaker muscles before TKA. Co-contraction was not significantly associated with patient function. Higher co-contraction was associated with weaker muscles across all time points. Knee laxity and balance were not strongly related to co-contraction. Future studies should investigate the effects of strength training programs on perceived instability in patients with OA. The relationship between co-contraction, strength, and function should be studied further. A larger study should be done to investigate the effects of knee balance and laxity on co-contraction after surgery.

Acknowledgements

I would like to begin by thanking my advisor, Dr. Robert Siston, for his help and encouragement during the past three and a half years. Had I not found his lab freshman year, I would have never gotten involved with undergraduate research. My work with him and everyone else in the NMBL has been one of the most fulfilling parts of my time at Ohio State.

I also want to thank all the NMBL members who have answered my questions and spent time helping me work through problems. Dr. Sarah Roelker, who was my mentor when I first started in the lab, spent countless hours gathering articles for me to read and teaching me how to use OpenSim and Vicon. Rachel Hall helped me solve lots of software issues that otherwise would have prevented me from completing this project. Rebekah, Anna, Brooke, Becca, Marisa, Megan, and Kaden were always willing to let me bounce ideas and questions off of them.

I finally want to thank my family and friends for being there for me for the past four years. I am grateful for their support, their company, and their faith in me every day.

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Chapter 1: Introduction

1.1 Background

Incidence of Osteoarthritis

Arthritis is a joint disease affecting more than 50 million Americans. This number is only expected to grow, and it is projected that 78.4 million U.S. adults will have arthritis by the year 2040 [1]. Osteoarthritis (OA) is the most common form of arthritis and the leading cause of pain and disability in elderly people worldwide [2]. It occurs most often in the knee joint, where the disease causes the breakdown of cartilage, growth of bone spurs, and narrowing of the joint space [3]. An illustration of a healthy (left) and an osteoarthritic (right) knee can be seen below (Figure 1).

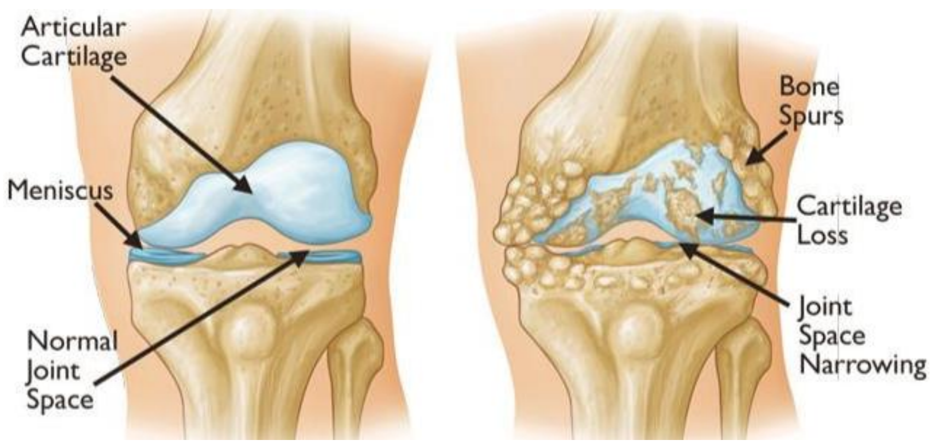

Figure 1: Healthy (left) and Osteoarthritic (right) Knee [4]

Osteoarthritis most commonly develops in people aged 50 years or older and gradually worsens over time. One study reported that the lifetime risk of developing knee OA was 44.7%, with that number increasing to 56.8% in individuals who had suffered a previous knee injury [5]. Patients with knee OA tend to experience knee pain, swelling, and stiffness, as well as muscle weakness, all of which lead to a reduced quality of life [6].

Perceived Instability

Beyond these symptoms, individuals with knee OA also tend to experience a feeling of instability that can affect their daily lives. Over 60% of patients with knee OA report perceived instability, defined as the feeling of “giving way”, buckling, or shifting of the knee [3], 7, 8]. Self-reported knee instability has been found to be related to activity limitations, increased pain, and decreased quality of life in this population [8].

Muscular Co-Contraction

Many patients with knee OA also exhibit elevated co-contraction levels [6].This muscle activation strategy is depicted in Figure 2. During walking, some muscles, like the quadriceps group, work to extend the knee, while others, like the hamstrings group, work to flex the knee. During co-contraction, these muscles activate at the same time. It has been suggested that patients with OA may be subconsciously utilizing co-contraction as a stabilization strategy [9, 10, 11]. It makes intuitive sense, then, that this strategy may be a response to the perception of instability that many patients with OA report. However, co-contraction stiffens and increases stress on the joint, further narrowing the joint space and leading to the progression of osteoarthritis [6]. How this muscle activation strategy relates to patient function remains unknown.

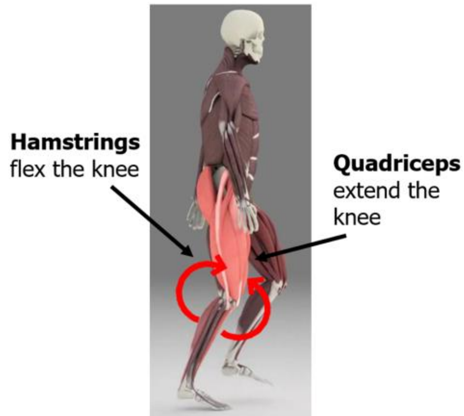

Figure 2: Co-contraction About the Knee

Treatment for Knee OA- Total Knee Arthroplasty

In cases of advanced OA, a total knee arthroplasty (TKA) is often performed to alleviate the patient's symptoms (Figure 3). During this procedure the damaged cartilage in the knee is removed, along with some of the femur and tibia [4]. The bones are then resurfaced with a metal component [4]. In most cases, the kneecap is resurfaced as well [4]. After this, a plastic spacer is inserted between the metal components [4]. The surgeon then aligns the femur and tibia and proceeds to make adjustments to the ligaments around the knee. These adjustments known as "soft-tissue balancing" are done to ensure that the patient's knee is neither too loose nor too tight, and will remain aligned in both flexion and extension. Inadequate soft-tissue balancing can lead to instability, stiffness, or excessive wear on the prosthetic [12].

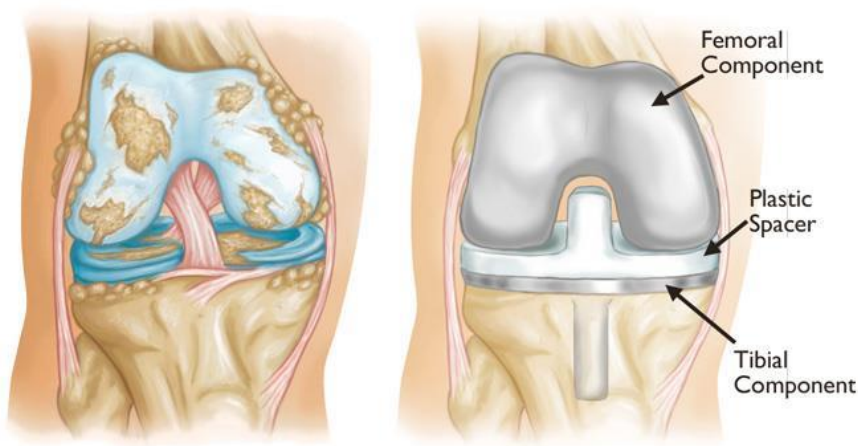

Figure 3: Advanced Osteoarthritic Knee (left) and Knee After TKA (right) [4]

Outcomes of TKA

Over 600,000 TKAs are performed in the United States each year [13], and this number is expected to rise to almost 3.5 million procedures annually by the year 2030 [14]. While the procedure generally results in reduced pain and improved function, problems with surgical outcomes remain. As many as 25% of patients report being dissatisfied with their surgical outcome [15]. Patients after TKA still walk and climb stairs more slowly, have weaker quadriceps compared to their peers [12], and utilize the co-contraction strategy [11]. Patients also report knee instability that persists after surgery [8].

Factors Affecting Perceived Instability

It is unknown why some patients continue to feel unstable after TKA, while others do not. During movement, knee stability is dependent upon both passive and active stabilizers. The major ligaments around the knee (Figure 4) provide most of its passive stability. These ligaments prevent excessive movement and keep the joint in place.

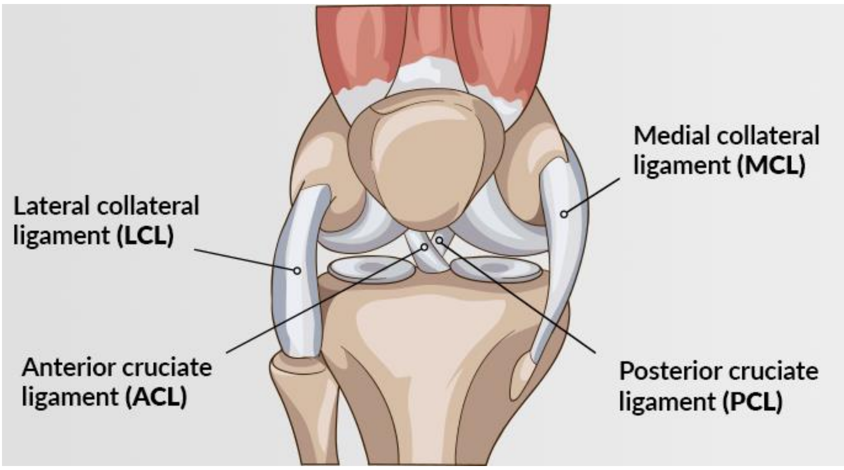

Figure 4: Major Ligaments in the Knee [18]

The muscles that cross the knee, including the quadriceps, hamstrings, and gastrocnemii (Figure 5), provide active stability, which can be augmented by co-contraction.

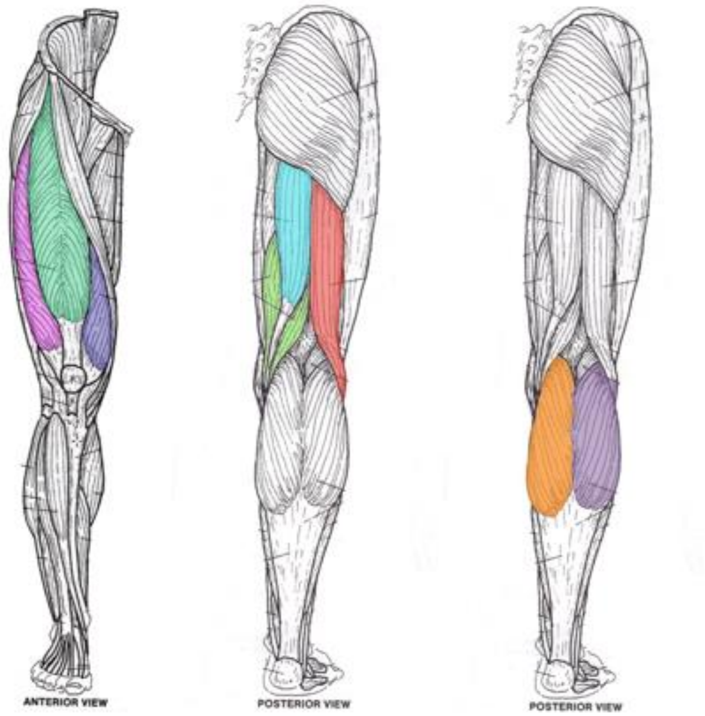

Figure 5: Quadriceps, Hamstrings, and Gastrocnemii

Patients who have undergone TKA experience changes in their stabilizing ligaments after soft tissue balancing. Patients also experience a loss of muscle strength and an increase in co-contraction after surgery [11]. Any number and combination of these factors may affect their perception of instability.

Knee Laxity

In order to understand how the changes in passive knee stability caused by soft tissue balancing may affect perceived instability, there must be a way to quantify passive knee stability. One way to do this is by measuring knee laxity, or knee motion under an applied load. This research focuses on knee laxity in the frontal plane (Figure 6), as increased varus-valgus laxity is a common symptom of knee OA [19].

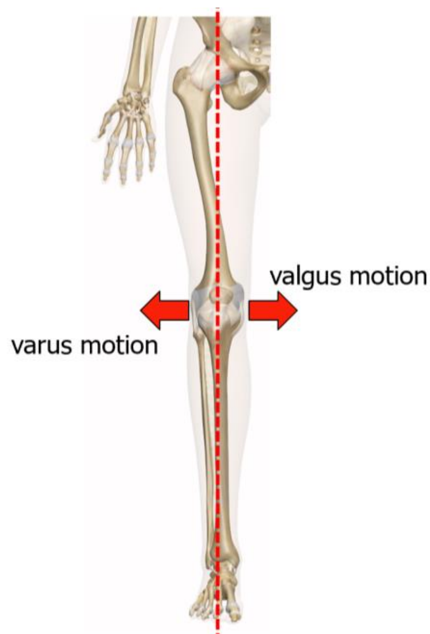

Figure 6: Varus and Valgus Motion of the Knee Joint

Previous Studies on Laxity, Strength, Co-contraction, Instability, and Function

Researchers have previously investigated relationships between laxity, strength, perceived instability, and co-contraction in OA patients before TKA. One study found that weaker knee muscles were associated with greater perceived instability in patients awaiting TKA [20]. Another study found that perceived instability, co-contraction, and knee laxity were unrelated before surgery [21]. It remains unknown how perceived instability is related to strength, co-contraction, and knee laxity after surgery.

1.2 Focus of Thesis

This research is focused on patients' perception of instability before and after TKA. It investigates factors that may be related to perceived instability, including co-contraction, strength, and passive knee laxity and balance. It also attempts to relate the co-contraction strategy to patients' function before and after surgery.

1.3 Significance of Research

Identifying these relationships is an important step in providing patients, surgeons, and clinicians with insight into the variables that affect TKA outcomes. This research could help provide patients with better expectations of their own surgical outcomes. It could also guide clinicians and surgeons to develop treatment plans, specifically therapy and surgical intervention, which will lead to better outcomes for their patients.

1.4 Overview of Thesis

This thesis contains five chapters. This first chapter introduces the project. The second chapter explains data collection and statistical analysis methods. The third chapter includes the results of the statistical analysis. The fourth chapter contains analysis and discussion of these results. The fifth chapter presents conclusions from this project and suggestions for future work.

Chapter 2: Methods

2.1 Experimental Data

Subject Demographics

Forty-three patients (15 male, 28 female, age=60.1±7.4 years, height=1672.0±104.3 mm, BMI=33.83±5.3) scheduled for TKA within 8 weeks, were recruited and provided IRB-approved consent as part of a larger project. Data were collected prior to surgery, as well as an average of 215 days and 783 days after surgery (referred to here as the pre-operative, 6 months post-operative, and 2 years post-operative groups).

Intra-Operative Data Collection

Passive knee kinematics were measured by the operating surgeon during TKA, while the patient was under general anesthesia. The experimental setup can be seen in Figure 7. After opening the knee, retro-reflective markers were attached to the exposed femur and tibia using bone screws. The patient's leg was fitted into a boot connected to a custom knee stability testing device [22]. The surgeon applied a moment to the knee via the force application handle. A custom surgical navigation system tracked the motion of the markers to determine the movement of the tibia and femur under this load [23].

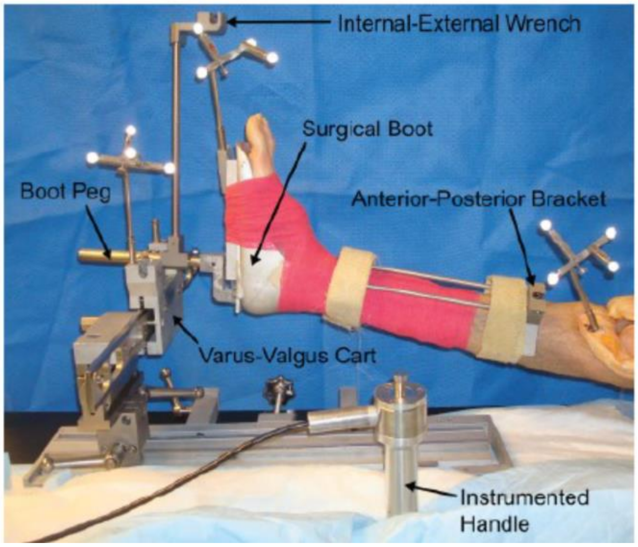

Figure 7: Surgical Boot and Tibial Markers on a Cadaveric Specimen [22]

I used two different measures of knee motion under an applied load: laxity and balance (Figure 8). Laxity was calculated as the total range of knee motion under the maximum varus and valgus loads applied. Knee balance was calculated as the maximum varus excursion minus the maximum valgus excursion. Measurements were taken before and after prosthetic implantation. A posterior-stabilized implant (NexGen LPS Flex, Zimmer, Inc., Warsaw, IN) was used in all patients.

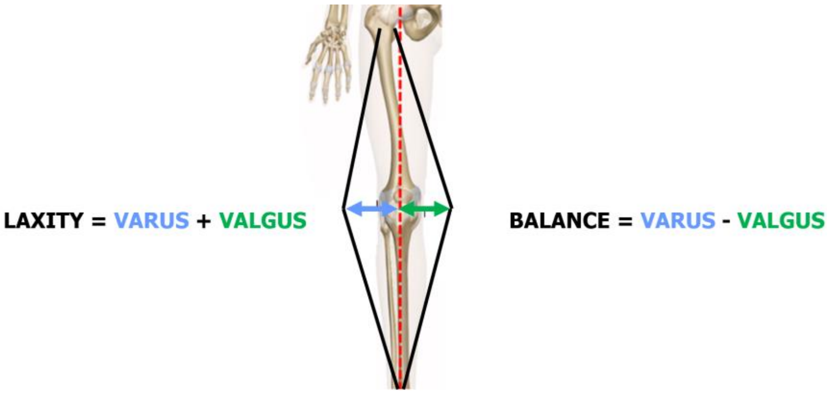

Figure 8: Knee Laxity and Knee Balance

Gait Lab Data Collection

Three-dimensional motion capture data were collected in Ohio State's Movement Analysis and Performance (MAP) Lab. Markers were applied to patients using the modified point-cluster technique [24]. Motion capture data were collected at 150 Hz using 10 Vicon MX-F40 cameras (Vicon; Oxford, UK) and filtered using a fourth-order Butterworth filter at 6 Hz. Ground reaction forces were collected using Bertec 4060-10 force plates (Bertec Corp; Columbus, OH) at 1,500 Hz. I processed the motion capture data for gait trials of patients two years after TKA. When there were gaps in the trials (when a marker was covered by clothing or skin, or not picked up by the cameras), I filled them using a spline or pattern-following technique. After running several processing pipelines, I used a custom Matlab script to pull and store the relevant data from a single walking trial for each patient. Most of the remaining motion capture data were processed previously by students in the Neuromuscular Biomechanics Lab and the MAP Lab.

Wireless surface electromyography (EMG) data (Telemyo DTS; Noraxon USA, Inc; Scottsdale, AZ) were measured on both limbs for each patient. EMG was recorded for the rectus femoris, vastus medialis, vastus lateralis, semitendinosus, biceps femoris long head, medial gastrocnemius, lateral gastrocnemius, and soleus. Raw EMG data were collected at 1500 Hz and filtered through a high pass, zero-lag fourth-order Butterworth filter at 10 Hz. Then, the EMG data were full-wave rectified and root-mean-squared filtered. Because pathological populations often have difficultly completing a MVIC, EMG signals from the walking trials were normalized using submaximal reference activities.

Strength Measurements

Knee muscle strength was measured as isometric knee extension and flexion strength. These data were collected for each patient using a Biodex System 3 dynamometer (Biodex Medical Systems; Shirley, NY), during a maximal voluntary isometric contraction (MVIC). The maximum torque produced during each MVIC was recorded and normalized by patient mass.

Measurements of Patient Function

The measures of patient function used in this research can be divided into two categories: performance-based and self-reported. Each patient's performance on three clinical tests commonly used in OA and TKA patients was recorded. The six-minute walk test (6MW) measures the distance a patient is able to walk within six minutes [25]. The stair-climbing test (SCT) measures the time it takes a patient to ascend and descend a set of twelve stairs [26]. The timed up-and-go test (TUG) measures the time it takes a patient to rise from a chair, walk three meters, turn around, and return to a seated position in the same chair [16].

Self-reported functional data were collected from questionnaires administered to the patients. The MOS 36-Item Short-Form Health Survey (SF-36) was administered and used as a measure of overall health and function [27]. From this test, two scores were obtained per patient: a Physical Component Score (PCS) and a Mental Component Score (MCS). The Knee Injury and Osteoarthritis Outcome Score (KOOS) was used to assess self-reported function related to the knee. Four KOOS subscales were assessed individually: pain, symptoms, activities of daily living, and knee related quality of life. Patients scored themselves on a scale of 0 to 4, based on given standardized answers (one answer related to each of 5 possible number scores) [28]. The scores were then normalized for each subscale, resulting in a final score of 0 (extreme symptoms) to 100 (no symptoms) for each subscale.

Perceived instability was measured by a question on the Knee Outcome Survey-Activities of Daily Living Scale: "To what degree does giving way, buckling, or shifting of the knee affect your daily activity?" [29]. Patients answered on a six-point scale, with 0 indicating that instability prevents all activity and 5 indicating no instability.

2.2 Co-Contraction Calculation

Co-Contraction Formula

This research uses four co-contraction indices (CCI) to measure co-contraction about the knee. These include: medial quadriceps/medial hamstrings (MQMH), lateral quadriceps/lateral hamstrings (LQLH), medial quadriceps/medial gastrocnemius (MQMG), and lateral quadriceps/lateral gastrocnemius (LQLG). For each patient, these indices are calculated for one representative gait trial. The CCI's are calculated using the equation below [Equation 1] [10]:

$$CCI = \frac{\left[\sum_{i=1}^{n} \frac{lower\ EMG_i}{higher\ EMG_i}(lower\ EMG_i + higher\ EMG_i\right]}{n}$$

Equation 1

In this equation, 'n' is the number of time points during the trial at which the equation is evaluated. 'Lower EMG' refers to the muscle with a lower activation magnitude, and 'higher EMG' refers to the muscle with a greater activation magnitude. This equation accounts for both the timing and magnitude of the opposing muscle pairs, as opposed to only computing a ratio or using average activations over one gait cycle. I calculated these co-contraction indices during each patient's weight acceptance phase, stance phase, and total gait cycle. Weight acceptance was defined as the portion of the gait cycle from heel strike of the involved limb to peak knee flexion angle [24]. Stance was defined as heel strike of the involved limb to toe-off. The EMG processing and co-contraction calculations were completed using a custom MATLAB script that I adapted for this project, based on a code written by Dr. Gregory Freisinger.

2.3 Analysis

Statistical Tests

Minitab Statistical Software (Version 17; Minitab Inc.; State College, PA) was used for all statistical analysis. Anderson-Darling tests were used to determine the normality of each data set. Since nearly all sets were non-normal, Spearman correlations were used to determine relationships between variables of interest. These correlation tests were run at each time point (before, six months after TKA, two years after TKA) individually. To determine change in co-contraction, strength, and perceived instability in patients over time, Freidman tests were used. These tests only included patients for which I had data at all three time points.

Chapter 3: Results

3.1 Perceived Instability and Co-contraction, Strength, Balance, and Laxity

Data Summary

A summary of the data analyzed in this section is included below (Table 1). Because perceived instability is not a continuous variable, only the median value is included for each time point. For co-contraction indices, strength, knee balance, and knee laxity, mean and standard deviation is included.

Table 1: Perceived Instability, Co-Contraction, Strength, Knee Balance, and Knee Laxity

Pre-Operative		6 Months Post-Operative		2 Years Post-Operative	
	Median		Median		Median
Perceived Instability	2	Perceived Instability	5	Perceived Instability	5
CCI	Mean ±std	CCI	Mean ±std	CCI	Mean ±std
Weight Acceptance		Weight Acceptance		Weight Acceptance	
MQMH	0.7190±0.5278	MQMH	0.7184±0.5364	MQMH	0.7161±0.5302
LQLH	1.0874±0.7455	LQLH	1.0646±0.7413	LQLH	1.0801±0.7477
MQMG	0.3338±0.3013	MQMG	0.3410±0.3039	MQMG	0.3313±0.3001
LQLG	0.4142±0.3365	LQLG	0.4170±0.3398	LQLG	0.4110±0.3344
Stance		Stance		Stance	
MQMH	0.3759±0.2678	MQMH	0.3752±0.2721	MQMH	0.3756±0.2688
LQLH	0.5498±0.3498	LQLH	0.5381±0.3415	LQLH	0.5492±0.3507
MQMG	0.3024±0.1708	MQMG	0.3069±0.1716	MQMG	0.3003±0.1719
LQLG	0.3447±0.1916	LQLG	0.3442±0.1945	LQLG	0.3400±0.1920
Strength (N-m/kg)	Mean ±std	Strength (N-m/kg)	Mean ±std	Strength (N-m/kg)	Mean ±std
Knee Extensors	0.9638±0.4390	Knee Extensors	1.0780±0.4367	Knee Extensors	1.2354±0.4581
Knee Flexors	0.5302±0.2486	Knee Flexors	0.5347±0.2700	Knee Flexors	0.6292±0.2489
Intra-Operative Measurements (degrees)	Mean ±std	Intra-Operative Measurements (degrees)	Mean ±std	Intra-Operative Measurements (degrees)	Mean ±std
Knee Balance	-0.4714±3.226	Knee Balance	-0.1405±2.9872	Knee Balance	-0.0963±3.7862
Knee Laxity	6.8190±2.8419	Knee Laxity	7.7810±3.3031	Knee Laxity	7.3216±3.6870

Pre-Operatively

For the pre-operative data, I compared perceived instability to co-contraction during the weight acceptance phase and the stance phase (denoted by the subscripts ‘wa’ and ‘stance’) and normalized knee extensor and flexor strength. I also compared perceived instability to knee balance and laxity measurements taken before prosthetic implantation. The results are summarized in Table 2. Higher MQMH co-contraction during the weight acceptance phase and the stance phase was associated with greater perceived instability. Higher knee extensor and flexor strength were associated with less perceived instability. Perceived instability was not associated with either knee balance or knee laxity.

Table 2: Perceived Instability and Co-contraction, Strength, and Knee Balance and Laxity Before TKA

	Spearman’s Rho	P-Value
Co-contraction to Perceived Instability		
$MQMH_{wa}$[b]	**-0.381**	**0.017**
$LQLH_{wa}$[d]	0.067	0.706
$MQMG_{wa}$[a]	0.155	0.345
$LQLG_{wa}$[b]	0.017	0.920
$MQMH_{stance}$[b]	**-0.452**	**0.004**
$LQLH_{stance}$[d]	-0.084	0.637
$MQMG_{stance}$[a]	0.053	0.751
$LQLG_{stance}$[b]	-0.194	0.243
Strength to Perceived Instability		
Knee Extensors[c]	**0.431**	**0.008**
Knee Flexors[c]	**0.435**	**0.007**
Intra-Operative Measurements to Perceived Instability		
Knee Balance[e]	-0.149	0.425
Knee Laxity[e]	0.271	0.140
a: n=39, b: n=38, c: n=37, d: n=33, e: n=31		

Post-Operatively

Post-operatively, I ran the same tests, but with knee balance and laxity measurements taken after prosthetic implantation. At the 6-month time point, no relationships were statistically significant (Table 3). At the 2-year time point, higher LQLG co-contraction during the weight acceptance phase was associated with less perceived instability (Table 4). However, looking at a scatter plot of that data, it appears that there is not any relationship between co-contraction and perceived instability (Figure 9).

Table 3: Perceived Instability and Co-contraction, Strength, and Knee Balance and Laxity 6 Months After TKA

	Spearman's Rho	P-Value
Co-contraction to Perceived Instability		
$MQMH_{wa}$[c]	-0.055	0.779
$LQLH_{wa}$[c]	-0.116	0.549
$MQMG_{wa}$[b]	0.053	0.781
$LQLG_{wa}$[a]	0.122	0.514
$MQMH_{stance}$[c]	-0.054	0.780
$LQLH_{stance}$[c]	0.020	0.918
$MQMG_{stance}$[b]	0.179	0.344
$LQLG_{stance}$[a]	0.286	0.119
Strength to Perceived Instability		
Knee Extensors[b]	0.209	0.267
Knee Flexors[b]	0.121	0.523
Intra-Operative Measurements to Perceived Instability		
Knee Balance[d]	-0.243	0.222
Knee Laxity[d]	-0.026	0.899
a: n=31, b: n=30, c: n=29, d: n=25		

Table 4: Perceived Instability and Co-contraction, Strength, and Knee Balance and Laxity 2 Years After TKA

	Spearman's Rho	P-Value
Co-contraction to Perceived Instability		
$MQMH_{wa}$[a]	-0.199	0.414
$LQLH_{wa}$[a]	0.156	0.523
$MQMG_{wa}$[b]	-0.084	0.740
$LQLG_{wa}$[a]	**0.485**	**0.035**
$MQMH_{stance}$[a]	-0.161	0.512
$LQLH_{stance}$[a]	-0.073	0.767
$MQMG_{stance}$[b]	-0.249	0.319
$LQLG_{stance}$[a]	-0.128	0.600
Strength to Perceived Instability		
Knee Extensors[b]	0.213	0.395
Knee Flexors[b]	0.095	0.708
Intra-Operative Measurements to Perceived Instability		
Knee Balance[b]	-0.406	0.119
Knee Laxity[b]	-0.14	0.605
a: n=19, b: n=18		

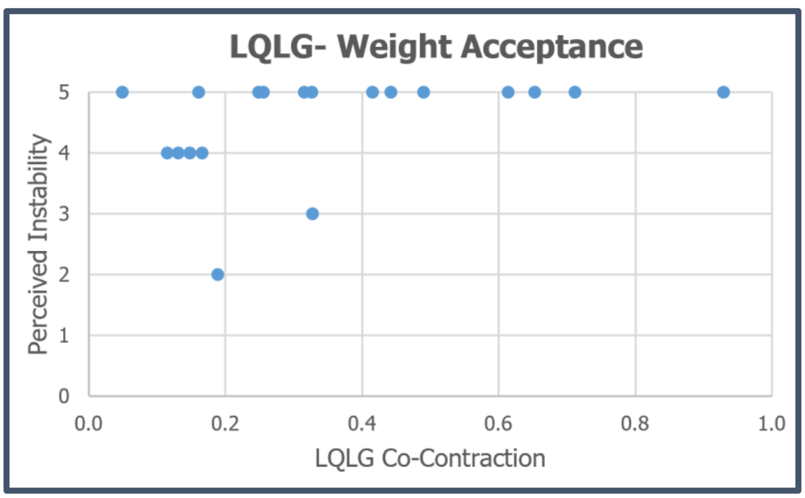

Figure 9: Perceived Instability vs. Co-contraction, 2 Years After TKA

Over Time

Due to loss of patients in the study, there were only 12 patients with valid data available for all three time points. I performed Freidman's tests to determine whether co-contraction, strength, and perceived instability changed with time. None of the co-contraction indices or strength measurements changed significantly over time. Perceived instability decreased with time ($p < 0.001$) (Figure 10).

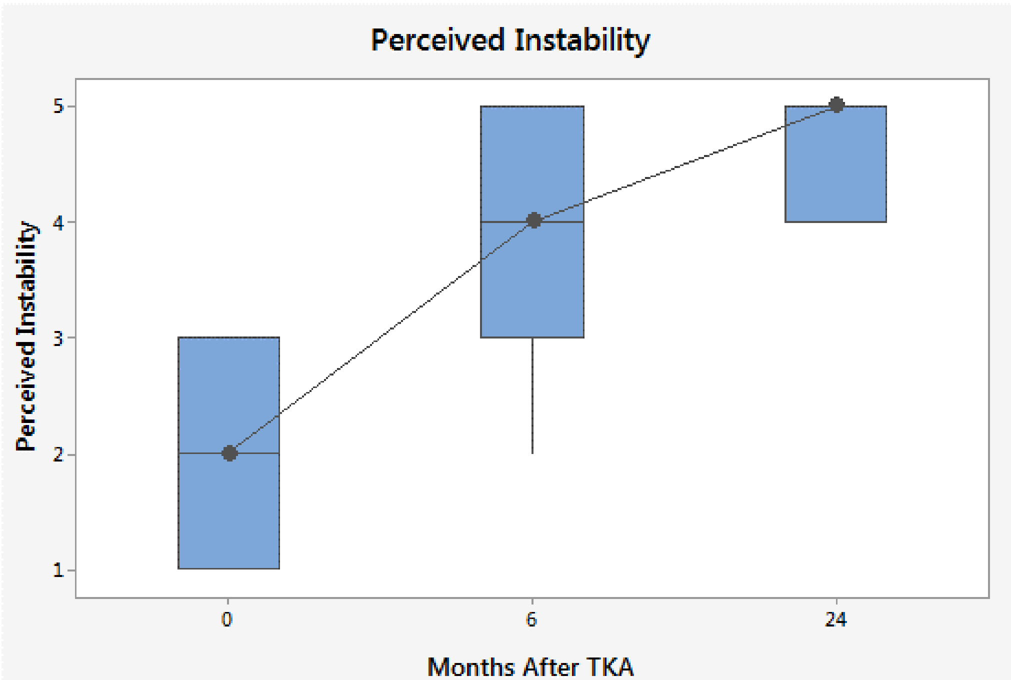

Figure 10: Boxplot of Perceived Instability, Grouped by Time (Median Connection Line Shown)

3.2 Co-Contraction and Patient Function

Co-contraction Indices

The co-contraction indices are summarized in Table 5 below. Co-contraction indices were generally higher for each muscle pair during the weight acceptance phase than they were for stance or total gait cycle. Lateral co-contraction was generally higher than medial co-

contraction. The spread of co-contraction indices for each group was not significantly different between time points.

Table 5: Co-Contraction Indices

Before TKA		6 Months After TKA		2 Years After TKA	
CCI	Mean ±std	CCI	Mean ±std	CCI	Mean ±std
Weight Acceptance		Weight Acceptance		Weight Acceptance	
MQMH	0.7190±0.5278	MQMH	0.7184±0.5364	MQMH	0.7161±0.5302
LQLH	1.0874±0.7455	LQLH	1.0646±0.7413	LQLH	1.0801±0.7477
MQMG	0.3338±0.3013	MQMG	0.3410±0.3039	MQMG	0.3313±0.3001
LQLG	0.4142±0.3365	LQLG	0.4170±0.3398	LQLG	0.4110±0.3344
Stance		Stance		Stance	
MQMH	0.3759±0.2678	MQMH	0.3752±0.2721	MQMH	0.3756±0.2688
LQLH	0.5498±0.3498	LQLH	0.5381±0.3415	LQLH	0.5492±0.3507
MQMG	0.3024±0.1708	MQMG	0.3069±0.1716	MQMG	0.3003±0.1719
LQLG	0.3447±0.1916	LQLG	0.3442±0.1945	LQLG	0.3400±0.1920
Total Gait Cycle		Total Gait Cycle		Total Gait Cycle	
MQMH	0.4666±0.4358	MQMH	0.4660±0.4436	MQMH	0.4686±0.4375
LQLH	0.6628±0.5293	LQLH	0.6458±0.5318	LQLH	0.6685±0.5312
MQMG	0.2828±0.1803	MQMG	0.2865±0.1819	MQMG	0.2808±0.1809
LQLG	0.3581±0.3315	LQLG	0.3564±0.3360	LQLG	0.3541±0.3330

Total Gait Cycle Co-Contraction and Patient Function

Initially, I compared total gait cycle co-contraction to patient function. The results of the statistical analysis are shown in Table 6, with statistically significant results shown in bold. Before TKA, higher MQMH, LQLH, and MQMG co-contraction were associated with a shorter 6MW distance. Higher MQMH and LQLH co-contraction were associated with a longer SCT. Higher MQMH co-contraction was associated with worse scores on both the KOOS ADL subscale and the SF-36 PCS. Six months after TKA, higher LQLH co-contraction was associated with a shorter 6MW distance. Higher MQMH and LQLH co-contraction were associated with a longer SCT. Two years after TKA, higher LQLG co-contraction was associated with a worse SF36- PCS.

Table 6: Correlations Between Total Gait Cycle Co-contraction and Patient Function

Before TKA	Spearman's Rho	P-Value	6 Months After TKA	Spearman's Rho	P-Value	2 Years After TKA	Spearman's Rho	P-Value
6MW			6MW			6MW		
MQMH[b]	**-0.502**	**0.004**	MQMH[b*]	-0.294	0.122	MQMH[e*]	0.051	0.836
LQLH[e]	**-0.484**	**0.001**	**LQLH [b*]**	**-0.375**	**0.045**	LQLH[e*]	-0.191	0.433
MQMG[a]	**-0.009**	**0.037**	MQMG[a*]	-0.133	0.484	MQMG[f*]	0.148	0.559
LQLG[b]	-0.339	0.957	LQLG[g]	-0.318	0.081	LQLG[e*]	-0.160	0.514
TUG			TUG			TUG		
MQMH[d]	0.147	0.392	MQMH[c*]	0.086	0.662	MQMH[f*]	-0.198	0.416
LQLH[f]	0.337	0.064	LQLH[c*]	0.252	0.196	LQLH[f*]	0.007	0.977
MQMG[c]	-0.130	0.443	MQMG[b*]	-0.120	0.535	MQMG[g*]	-0.331	0.179
LQLG[d]	0.216	0.205	LQLG[a*]	0.156	0.412	LQLG[f*]	0.100	0.684
SCT			SCT			SCT		
MQMH[b]	**0.402**	**0.012**	**MQMH[b*]**	**0.368**	**0.050**	MQMH[e*]	-0.258	0.286
LQLH[e]	**0.346**	**0.048**	**LQLH[b*]**	**0.470**	**0.010**	LQLH[e*]	0.032	0.898
MQMG[a]	0.147	0.371	MQMG[a*]	0.132	0.487	MQMG[f*]	-0.191	0.448
LQLG[b]	0.264	0.109	LQLG[g]	0.330	0.070	LQLG[e*]	0.035	0.887
KOOS- Pain			KOOS- Pain			KOOS- Pain		
MQMH[b]	-0.255	0.117	MQMH[b*]	-0.276	0.147	MQMH[e*]	0.178	0.465
LQLH[e]	-0.065	0.716	LQLH[b*]	-0.209	0.277	LQLH[e*]	-0.318	0.185
MQMG[a]	0.014	0.930	MQMG[a*]	0.065	0.733	MQMG[f*]	-0.037	0.883
LQLG[b]	-0.143	0.384	LQLG[g]	-0.076	0.685	LQLG[e*]	-0.209	0.390
KOOS- Symptoms			KOOS- Symptoms			KOOS- Symptoms		
MQMH[b]	-0.160	0.331	MQMH[b*]	-0.071	0.718	MQMH[e*]	0.330	0.168
LQLH[e]	-0.247	0.159	LQLH[b*]	-0.296	0.126	LQLH[e*]	0.009	0.971
MQMG[a]	-0.212	0.188	MQMG[a*]	0.130	0.500	MQMG[f*]	0.189	0.454
LQLG[b]	-0.275	0.091	LQLG[g]	-0.177	0.538	LQLG[e*]	0.082	0.739
KOOS- ADL			KOOS- ADL			KOOS- ADL		
MQMH[b]	**-0.317**	**0.050**	MQMH[b*]	-0.221	0.249	MQMH[e*]	0.181	0.472
LQLH[e]	-0.100	0.574	LQLH[b*]	-0.200	0.299	LQLH[e*]	-0.232	0.355
MQMG[a]	-0.077	0.192	MQMG[a*]	0.042	0.826	MQMG[f*]	-0.009	0.974
LQLG[b]	-0.213	0.638	LQLG[g]	-0.172	0.355	LQLG[e*]	-0.128	0.612
KOOS- QoL			KOOS- QoL			KOOS- QoL		
MQMH[b]	-0.303	0.061	MQMH[b*]	-0.212	0.270	MQMH[e*]	0.207	0.411
LQLH[e]	-0.061	0.733	LQLH[b*]	-0.153	0.429	LQLH[e*]	-0.339	0.168
MQMG[a]	0.000	0.999	MQMG[a*]	0.021	0.912	MQMG[f*]	0.133	0.611
LQLG[b]	-0.019	0.910	LQLG[g]	-0.105	0.573	LQLG[e*]	-0.160	0.526
SF36- PCS			SF36- PCS			SF36- PCS		
MQMH[b]	**-0.358**	**0.025**	MQMH[d*]	-0.289	0.144	MQMH[e*]	-0.026	0.915
LQLH[e]	-0.149	0.402	LQLH[d*]	-0.370	0.058	LQLH[e*]	-0.267	0.270
MQMG[a]	-0.185	0.568	MQMG[c*]	0.003	0.987	MQMG[f*]	0.245	0.328
LQLG[b]	-0.093	0.259	LQLG[b*]	-0.232	0.227	**LQLG[e*]**	**-0.488**	**0.034**
SF36- MCS			SF36- MCS			SF36- MCS		
MQMH[b]	-0.009	0.958	MQMH[d*]	0.195	0.329	MQMH[e*]	-0.016	0.949
LQLH[e]	0.191	0.279	LQLH[d*]	0.258	0.193	LQLH[e*]	0.086	0.726
MQMG[a]	0.164	0.311	MQMG[c*]	0.077	0.531	MQMG[f*]	-0.162	0.521
LQLG[b]	0.109	0.511	LQLG[b*]	0.121	0.698	LQLG[e*]	0.477	0.055

a: n=40, b: n=39, c: n=38, d: n=37, e: n=34, f: n=32, g: n=31, a*: n=30, b*: n=29, c*: n=28, d*: n=27, e*: n=19, f*: n=18, g*: n=17

While these data would suggest that co-contraction is at least weakly associated with worse function, scatter plots of the data reveal that a few outliers are likely throwing off the correlations (Figure 11). If the outliers aren't considered, the trend between increased co-contraction and reduced function is not nearly as evident.

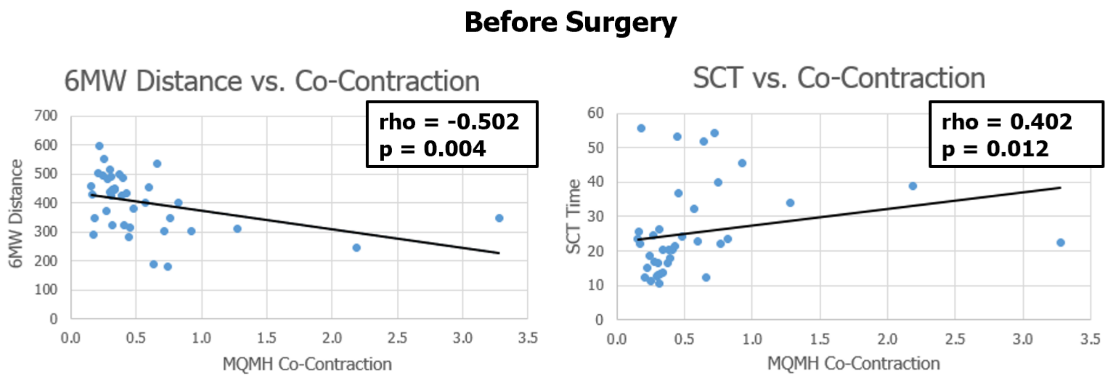

Figure 11: Co-Contraction and Performance-Based Function, Before TKA

Stance Phase Co-Contraction and Patient Function

After failing to see significant trends between patient function and total gait cycle co-contraction, I looked into the relationships between patient function and co-contraction during the stance and weight acceptance phases. The results of the analysis with stance phase co-contraction are included in Table 7. Before TKA, higher MQMH, LQLH, and LQLH co-contraction were associated with worse performance on the 6MW. Higher MQMH co-contraction was associated with worse performance on the SCT, a worse KOOS-ADL score, and a worse SF-36 PCS. Higher LQLG co-contraction was associated with a worse KOOS-Symptoms score. Six months after TKA, higher LQLH co-contraction was associated with worse performance on the SCT. Two years after TKA, higher MQMG co-contraction was associated with better performance on the TUG and a better SF-36 PCS.

Table 7: Correlations Between Stance Phase Co-contraction and Patient Function

Before TKA	Spearman's Rho	P-Value	6 Months After TKA	Spearman's Rho	P-Value	2 Years After TKA	Spearman's Rho	P-Value
6MW			6MW			6MW		
MQMH[b]	**-0.463**	**0.003**	MQMH[b*]	-0.329	0.081	MQMH[e*]	0.202	0.408
LQLH[e]	**-0.400**	**0.021**	LQLH[b*]	-0.340	0.071	LQLH[e*]	-0.125	0.611
MQMG[a]	0.026	0.874	MQMG[a*]	-0.162	0.392	MQMG[f*]	0.232	0.354
LQLG[b]	**-0.369**	**0.023**	LQLG[g]	-0.340	0.062	LQLG[e*]	-0.084	0.732
TUG			TUG			TUG		
MQMH[d]	0.272	0.109	MQMH[c*]	0.157	0.425	MQMH[f*]	-0.089	0.716
LQLH[f]	0.301	0.100	LQLH[c*]	0.284	0.143	LQLH[f*]	0.014	0.955
MQMG[c]	-0.188	0.265	MQMG[b*]	-0.028	0.887	**MQMG[g*]**	**-0.608**	**0.007**
LQLG[d]	0.224	0.190	LQLG[a*]	0.264	0.159	LQLG[f*]	-0.128	0.601
SCT			SCT			SCT		
MQMH[b]	**0.448**	**0.005**	MQMH[b*]	0.347	0.065	MQMH[e*]	-0.300	0.212
LQLH[e]	0.294	0.097	**LQLH[b*]**	**0.377**	**0.044**	LQLH[e*]	-0.109	0.658
MQMG[a]	0.080	0.627	MQMG[a*]	0.147	0.437	MQMG[f*]	-0.346	0.160
LQLG[b]	0.307	0.060	LQLG[g]	0.329	0.071	LQLG[e*]	-0.111	0.652
KOOS- Pain			KOOS- Pain			KOOS- Pain		
MQMH[b]	-0.295	0.068	MQMH[b*]	-0.104	0.590	MQMH[e*]	0.067	0.785
LQLH[e]	0.023	0.896	LQLH[b*]	0.043	0.825	LQLH[e*]	-0.363	0.127
MQMG[a]	0.034	0.834	MQMG[a*]	0.070	0.712	MQMG[f*]	-0.019	0.941
LQLG[b]	-0.160	0.330	LQLG[g]	0.045	0.812	LQLG[e*]	-0.126	0.607
KOOS-Symptoms			KOOS- Symptoms			KOOS- Symptoms		
MQMH[b]	-0.268	0.099	MQMH[b*]	-0.030	0.880	MQMH[e*]	0.356	0.135
LQLH[e]	-0.195	0.270	LQLH[b*]	-0.218	0.265	LQLH[e*]	0.122	0.620
MQMG[a]	-0.165	0.308	MQMG[a*]	-0.009	0.232	MQMG[f*]	0.127	0.614
LQLG[b]	**-0.341**	**0.034**	LQLG[g]	0.229	0.961	LQLG[e*]	0.018	0.943
KOOS- ADL			KOOS- ADL			KOOS- ADL		
MQMH[b]	**-0.392**	**0.014**	MQMH[b*]	-0.059	0.762	MQMH[e*]	0.178	0.480
LQLH[e]	-0.072	0.684	LQLH[b*]	0.010	0.960	LQLH[e*]	-0.247	0.323
MQMG[a]	-0.078	0.632	MQMG[a*]	0.078	0.682	MQMG[f*]	-0.081	0.757
LQLG[b]	-0.233	0.154	LQLG[g]	-0.054	0.771	LQLG[e*]	-0.056	0.826
KOOS- QoL			KOOS- QoL			KOOS- QoL		
MQMH[b]	-0.311	0.054	MQMH[b*]	0.001	0.996	MQMH[e*]	0.434	0.072
LQLH[e]	0.053	0.764	LQLH[b*]	0.116	0.548	LQLH[e*]	-0.125	0.622
MQMG[a]	0.056	0.730	MQMG[a*]	0.038	0.843	MQMG[f*]	0.085	0.746
LQLG[b]	-0.044	0.790	LQLG[g]	0.016	0.930	LQLG[e*]	-0.061	0.809
SF36- PCS			SF36- PCS			SF36- PCS		
MQMH[b]	**-0.432**	**0.006**	MQMH[d*]	-0.266	0.181	MQMH[e*]	-0.089	0.716
LQLH[e]	-0.134	0.449	LQLH[d*]	-0.211	0.290	LQLH[e*]	-0.154	0.528
MQMG[a]	-0.079	0.628	MQMG[c*]	-0.089	0.652	**MQMG[f*]**	**0.644**	**0.710**
LQLG[b]	-0.274	0.092	LQLG[b*]	-0.211	0.249	LQLG[e*]	0.091	0.003
SF36- MCS			SF36- MCS			SF36- MCS		
MQMH[b]	0.018	0.913	MQMH[d*]	0.271	0.171	MQMH[e*]	0.068	0.781
LQLH[e]	0.275	0.115	LQLH[d*]	0.322	0.101	LQLH[e*]	0.107	0.663
MQMG[a]	0.168	0.300	MQMG[c*]	0.027	0.892	MQMG[f*]	-0.292	0.240
LQLG[b]	0.085	0.606	LQLG[b*]	0.113	0.558	LQLG[e*]	0.204	0.403

a: n=40, b: n=39, c: n=38, d: n=37, e: n=34, f: n=32, g: n=31, a*: n=30, b*: n=29, c*: n=28, d*: n=27, e*: n=19, f*: n=18, g*: n=17

Weight Acceptance Phase Co-Contraction and Patient Function

The results of the analysis with weight acceptance phase co-contraction are included in Table 8. Before TKA, higher MQMH co-contraction was associated with worse performance on the 6MW and worse scores on the KOOS-ADL and SF-36 PCS. Six months after TKA, co-contraction was not related to any measures of function. Two years after TKA, higher MQMH co-contraction was related to better scores on the KOOS-ADL and KOOS-QoL subscales.

Table 8: Correlations Between Weight Acceptance Phase Co-contraction and Patient Function

Before TKA	Spearman's Rho	P-Value	6 Months After TKA	Spearman's Rho	P-Value	2 Years After TKA	Spearman's Rho	P-Value
6MW			6MW			6MW		
MQMH[b]	**-0.328**	**0.045**	MQMH[b*]	-0.130	0.503	MQMH[e*]	0.107	0.663
LQLH[e]	-0.194	0.278	LQLH [b*]	-0.236	0.217	LQLH[e*]	0.137	0.576
MQMG[a]	0.061	0.714	MQMG[a*]	-0.044	0.816	MQMG[f*]	0.209	0.404
LQLG[b]	-0.135	0.418	LQLG[g]	-0.276	0.132	LQLG[e*]	-0.037	0.881
TUG			TUG			TUG		
MQMH[d]	0.200	0.242	MQMH[c*]	0.004	0.985	MQMH[f*]	-0.161	0.509
LQLH[f]	0.147	0.429	LQLH[c*]	0.140	0.477	LQLH[f*]	-0.135	0.581
MQMG[c]	-0.174	0.304	MQMG[b*]	-0.169	0.381	MQMG[g*]	-0.220	0.381
LQLG[d]	0.058	0.735	LQLG[a*]	0.213	0.258	LQLG[f*]	0.107	0.663
SCT			SCT			SCT		
MQMH[b]	0.289	0.079	MQMH[b*]	0.221	0.249	MQMH[e*]	-0.179	0.464
LQLH[e]	0.026	0.884	LQLH[b*]	0.271	0.154	LQLH[e*]	-0.149	0.542
MQMG[a]	0.156	0.334	MQMG[a*]	0.027	0.886	MQMG[f*]	-0.133	0.598
LQLG[b]	0.191	0.249	LQLG[g]	0.150	0.419	LQLG[e*]	0.149	0.542
KOOS- Pain			KOOS- Pain			KOOS- Pain		
MQMH[b]	-0.204	0.213	MQMH[b*]	-0.116	0.548	MQMH[e*]	0.326	0.174
LQLH[e]	0.194	0.272	LQLH[b*]	-0.065	0.738	LQLH[e*]	0.080	0.744
MQMG[a]	0.176	0.278	MQMG[a*]	0.101	0.596	MQMG[f*]	-0.082	0.746
LQLG[b]	0.054	0.742	LQLG[g]	-0.027	0.885	LQLG[e*]	-0.110	0.966
KOOS-Symptoms			KOOS- Symptoms			KOOS- Symptoms		
MQMH[b]	-0.178	0.278	MQMH[b*]	0.073	0.712	MQMH[e*]	0.346	0.146
LQLH[e]	-0.075	0.672	LQLH[b*]	-0.193	0.325	LQLH[e*]	0.331	0.166
MQMG[a]	-0.027	0.868	MQMG[a*]	0.174	0.366	MQMG[f*]	0.203	0.419
LQLG[b]	-0.084	0.609	LQLG[g]	0.019	0.919	LQLG[e*]	0.108	0.659
KOOS- ADL			KOOS- ADL			KOOS- ADL		
MQMH[b]	**-0.324**	**0.045**	MQMH[b*]	-0.053	0.786	**MQMH[e*]**	**0.481**	**0.043**
LQLH[e]	0.139	0.433	LQLH[b*]	-0.032	0.868	LQLH[e*]	0.118	0.531
MQMG[a]	0.087	0.595	MQMG[a*]	0.106	0.579	MQMG[f*]	0.229	0.697
LQLG[b]	-0.012	0.944	LQLG[g]	-0.091	0.627	LQLG[e*]	0.036	0.506
KOOS- QoL			KOOS- QoL			KOOS- QoL		
MQMH[b]	-0.260	0.110	MQMH[b*]	0.003	0.988	**MQMH[e*]**	**0.554**	**0.017**
LQLH[e]	0.236	0.179	LQLH[b*]	-0.015	0.939	LQLH[e*]	0.118	0.640
MQMG[a]	0.190	0.239	MQMG[a*]	0.023	0.902	MQMG[f*]	0.229	0.376
LQLG[b]	0.211	0.198	LQLG[g]	0.049	0.793	LQLG[e*]	0.036	0.886
SF36- PCS			SF36- PCS			SF36- PCS		
MQMH[b]	**-0.345**	**0.032**	MQMH[d*]	-0.156	0.436	MQMH[e*]	-0.181	0.459
LQLH[e]	0.068	0.703	LQLH[d*]	-0.161	0.424	LQLH[e*]	-0.179	0.464
MQMG[a]	0.084	0.607	MQMG[c*]	0.080	0.684	MQMG[f*]	0.139	0.581
LQLG[b]	0.010	0.954	LQLG[b*]	-0.254	0.183	LQLG[e*]	-0.412	0.079
SF36- MCS			SF36- MCS			SF36- MCS		
MQMH[b]	0.028	0.867	MQMH[d*]	0.284	0.150	MQMH[e*]	0.181	0.459
LQLH[e]	0.149	0.401	LQLH[d*]	0.331	0.092	LQLH[e*]	0.311	0.196
MQMG[a]	0.236	0.143	MQMG[c*]	-0.053	0.791	MQMG[f*]	-0.091	0.723
LQLG[b]	0.243	0.136	LQLG[b*]	-0.044	0.821	**LQLG[e*]**	**0.540**	**0.017**

a: n=40, b: n=39, c: n=38, d: n=37, e: n=34, f: n=32, g: n=31, a*: n=30, b*: n=29, c*: n=28, d*: n=27, e*: n=19, f*: n=18, g*: n=17

Co-Contraction Differences Between Better/Worse 6MW Performance

The correlation tests did not reveal any clear relationship between co-contraction and function, so I ran Mann-Whitney Tests to determine whether patients with better 6MW performance utilized more or less co-contraction than patients who performed worse on the 6MW. For each time point, better performance was defined as having a 6MW distance that was above the mean for all the patients at that time point. The results of this analysis are summarized in Table 9. Before surgery, patients who performed worse on the 6MW utilized higher MQMH co-contraction during the weight acceptance phase, and higher MQMH, LQLH, and LQLG co-contraction during the stance phase. Six months after surgery, patients who performed worse on the 6MW utlized higher MQMG co-contraction during the weight acceptance phase. Two years after surgery, patients who performed worse on the 6MW did not utilize significantly different co-contraction than patients who performed better on the 6MW.

Table 9: Co-Contraction Between Better 6MW Performers and Worse 6MW Performers

Before TKA		6 Months After TKA		2 Years After TKA	
Index	P-Value	Index	P-Value	Index	P-Value
$MQMH_{wa}$	**0.0175**	$MQMH_{wa}$	0.9476	$MQMH_{wa}$	0.0758
$LQLH_{wa}$	0.0789	$LQLH_{wa}$	0.2114	$LQLH_{wa}$	0.3859
$MQMG_{wa}$	0.6967	**$MQMG_{wa}$**	**0.0091**	$MQMG_{wa}$	0.4501
$LQLG_{wa}$	0.2020	$LQLG_{wa}$	0.4389	$LQLG_{wa}$	0.7102
$MQMH_{stance}$	**0.0200**	$MQMH_{stance}$	0.4428	$MQMH_{stance}$	0.0523
$LQLH_{stance}$	**0.0012**	$LQLH_{stance}$	0.3028	$LQLH_{stance}$	0.9671
$MQMG_{stance}$	0.4785	$MQMG_{stance}$	0.6453	$MQMG_{stance}$	0.8242
$LQLG_{stance}$	**0.0145**	$LQLG_{stance}$	0.2416	$LQLG_{stance}$	0.6497
Better: n=22, Worse: n=17		Better: n=14, Worse: n=17		Better: n=11, Worse: n=8	

Co-Contraction and Peak Knee Flexion Angle

After all previous tests failed to identify a clear relationship between co-contraction and either performance-based or self-reported measures of function, I ran correlation tests on the relationship of co-contraction during the weight acceptance phase to peak knee flexion angle

(Table 10). Higher MQMH co-contraction was associated with a larger peak knee flexion angle 6 months after TKA. No other co-contraction indices were related to peak knee flexion angle at any time point.

Table 10: Co-Contraction and Peak Knee Flexion Angle

Before TKA			6 Months After TKA			2 Years After TKA		
Co-Contraction to Peak Knee Flexion Angle			Co-Contraction to Peak Knee Flexion Angle			Co-Contraction to Peak Knee Flexion Angle		
	Spearman's Rho	P-Value		Spearman's Rho	P-Value		Spearman's Rho	P-Value
$MQMH_{wa}$[a]	0.068	0.682	**$MQMH_{wa}$[d]**	**0.405**	**0.029**	$MQMH_{wa}$[f]	0.123	0.616
$LQLH_{wa}$[b]	-0.035	0.846	$LQLH_{wa}$[d]	0.217	0.259	$LQLH_{wa}$[f]	0.191	0.433
$MQMG_{wa}$[c]	0.067	0.682	$MQMG_{wa}$[e]	-0.057	0.764	$MQMG_{wa}$[g]	-0.356	0.147
$LQLG_{wa}$[a]	0.059	0.720	$LQLG_{wa}$[d]	0.215	0.247	$LQLG_{wa}$[f]	-0.107	0.663
a: n=39; b: n=34; c: n=40; d: n=29; e: n=30; f: n=19; g: n=18								

3.3 Co-contraction and Passive Knee Balance and Laxity, Strength

After testing the running the tests above, I was curious about whether co-contraction might be a response to excessive knee laxity or an imbalanced knee, or whether it may be related to strength. I used Spearman's correlations to determine the relationship of co-contraction during the weight acceptance and stance phases to knee laxity, knee balance, and strength, both before and after TKA.

Co-Contraction and Knee Laxity

The relationship of co-contraction to knee laxity is summarized below in Table 11. Co-contraction was unrelated to knee laxity before or six months after TKA. Two years after TKA, higher MQMH co-contraction during the weight acceptance phase was associated with greater knee laxity.

Table 11: Co-Contraction and Knee Laxity

Pre-Operative			6 Months Post-Operative			2 Years Post-Operative		
	Spearman's Rho	P-Value		Spearman's Rho	P-Value		Spearman's Rho	P-Value
$MQMH_{wa}^{b}$	0.15	0.42	$MQMH_{wa}^{e}$	0.031	0.884	**$MQMH_{wa}^{f}$**	**0.521**	**0.039**
$LQLH_{wa}^{e}$	0.01	0.962	$LQLH_{wa}^{e}$	-0.137	0.522	$LQLH_{wa}^{f}$	0.121	0.656
$MQMG_{wa}^{a}$	0.208	0.253	$MQMG_{wa}^{d}$	0.115	0.585	$MQMG_{wa}^{g}$	-0.104	0.713
$LQLG_{wa}^{b}$	0.01	0.957	$LQLG_{wa}^{c}$	0.142	0.489	$LQLG_{wa}^{f}$	-0.032	0.905
$MQMH_{stance}^{b}$	0.116	0.534	$MQMH_{stance}^{e}$	0.158	0.449	$MQMH_{stance}^{f}$	0.368	0.161
$LQLH_{stance}^{e}$	0.075	0.715	$LQLH_{stance}^{e}$	0.143	0.506	$LQLH_{stance}^{f}$	0.076	0.778
$MQMG_{stance}^{a}$	0.240	0.187	$MQMG_{stance}^{d}$	-0.128	0.541	$MQMG_{stance}^{g}$	-0.293	0.289
$LQLG_{stance}^{b}$	-0.047	0.802	$LQLG_{stance}^{c}$	-0.190	0.351	$LQLG_{stance}^{f}$	-0.091	0.737
a: n=34, b: n=33, c: n=30, d: n=29, e: n=28, f: n=18, g: n=17								

Co-Contraction and Knee Balance

The relationship of co-contraction to knee balance is summarized in Table 12. Before TKA, more valgus knee balance was related to higher LQLG co-contraction during the weight acceptance phase, and higher MQMG co-contraction during the stance phase. Six months after surgery, higher LQLH co-contraction during the weight acceptance phase was associated with a more valgus-balanced knee.

Table 12: Co-contraction and Knee Balance

Pre-Operative			6 Months Post-Operative			2 Years Post-Operative		
	Spearman's Rho	P-Value		Spearman's Rho	P-Value		Spearman's Rho	P-Value
$MQMH_{wa}^{b}$	0.037	0.844	$MQMH_{wa}^{e}$	0.011	0.956	$MQMH_{wa}^{f}$	-0.68	0.803
$LQLH_{wa}^{e}$	-0.296	0.142	**$LQLH_{wa}^{e}$**	**-0.433**	**0.031**	$LQLH_{wa}^{f}$	-0.224	0.405
$MQMG_{wa}^{a}$	-0.25	0.168	$MQMG_{wa}^{d}$	0.209	0.306	$MQMG_{wa}^{g}$	0.236	0.398
$LQLG_{wa}^{b}$	**-0.267**	**0.043**	$LQLG_{wa}^{c}$	0.329	0.094	$LQLG_{wa}^{f}$	-0.468	0.068
$MQMH_{stance}^{b}$	0.112	0.548	$MQMH_{stance}^{e}$	0.156	0.446	$MQMH_{stance}^{f}$	0.247	0.356
$LQLH_{stance}^{e}$	-0.121	0.556	$LQLH_{stance}^{e}$	-0.282	0.173	$LQLH_{stance}^{f}$	-0.315	0.984
$MQMG_{stance}^{a}$	**-0.352**	**0.048**	$MQMG_{stance}^{d}$	0.195	0.341	$MQMG_{stance}^{g}$	0.000	1.000
$LQLG_{stance}^{b}$	-0.353	0.051	$LQLG_{stance}^{c}$	0.159	0.427	$LQLG_{stance}^{f}$	-0.315	0.235
a: n=34, b: n=33, c: n=30, d: n=29, e: n=28, f: n=18, g: n=17								

Co-Contraction and Strength

The relationship of co-contraction during the weight acceptance phases, stance phase, and total gait cycle to strength is summarized below in Tables 13-15. Greater co-contraction was associated with weaker knee muscle strength at all time points, but most strongly before and six months after TKA.

Table 13: Co-Contraction and Strength Before TKA

Co-Contraction and Strength- Before TKA					
Knee Extensor Strength			Knee Flexor Strength		
	Spearman's Rho	P- Value		Spearman's Rho	P-Value
$LQLH_{wa}$[a]	-0.104	0.572	$LQLH_{wa}$[a]	-0.241	0.184
$MQMH_{wa}$[b]	-0.207	0.107	**$MQMH_{wa}$[b]**	**-0.364**	**0.027**
$LQLG_{wa}$[a]	-0.098	0.564	$LQLG_{wa}$[a]	-0.178	0.291
$MQMG_{wa}$[c]	-0.119	0.478	$MQMG_{wa}$[c]	-0.243	0.142
$LQLH_{s}$[a]	-0.277	0.125	**$LQLH_{s}$[a]**	**-0.462**	**0.008**
$MQMH_{s}$[b]	**-0.406**	**0.013**	**$MQMH_{s}$[b]**	**-0.504**	**0.001**
$LQLG_{s}$[a]	-0.232	0.166	$LQLG_{s}$[a]	-0.323	0.051
$MQMG_{s}$[c]	-0.177	0.287	**$MQMG_{s}$[c]**	**-0.323**	**0.048**
$LQLH_{t}$[a]	**-0.382**	**0.031**	**$LQLH_{t}$[a]**	**-0.507**	**0.003**
$MQMH_{t}$[b]	**-0.424**	**0.009**	**$MQMH_{t}$[b]**	**-0.517**	**0.001**
$LQLG_{t}$[a]	-0.227	0.177	**$LQLG_{t}$[a]**	**-0.286**	**0.086**
$MQMG_{t}$[c]	-0.163	0.327	$MQMG_{t}$[c]	-0.29	0.077
a: n=31; b: n=34; c: n=35					

Table 14: Co-Contraction and Strength 6 Months After TKA

Co-Contraction and Strength- Before TKA					
Knee Extensor Strength			Knee Flexor Strength		
	Spearman’s Rho	P- Value		Spearman’s Rho	P-Value
LQLH$_{wa}^{a}$	**-0.398**	**0.036**	**LQLH$_{wa}^{a}$**	**-0.379**	**0.047**
MQMH$_{wa}^{a}$	-0.205	0.295	MQMH$_{wa}^{a}$	-0.26	0.182
LQLG$_{wa}^{b}$	-0.216	0.252	LQLG$_{wa}^{b}$	-0.138	0.467
MQMG$_{wa}^{b}$	-0.117	0.545	MQMG$_{wa}^{b}$	-0.078	0.688
LQLH$_{s}^{a}$	**-0.527**	**0.004**	**LQLH$_{s}^{a}$**	**-0.584**	**0.001**
MQMH$_{s}^{a}$	-0.346	0.071	**MQMH$_{s}^{a}$**	**-0.446**	**0.017**
LQLG$_{s}^{b}$	**-0.440**	**0.015**	**LQLG$_{s}^{b}$**	**-0.471**	**0.009**
MQMG$_{s}^{b}$	-0.314	0.097	MQMG$_{s}^{b}$	-0.233	0.223
LQLH$_{t}^{a}$	**-0.539**	**0.003**	**LQLH$_{t}^{a}$**	**-0.59**	**0.001**
MQMH$_{t}^{a}$	**-0.418**	**0.027**	**MQMH$_{t}^{a}$**	**-0.447**	**0.017**
LQLG$_{t}^{b}$	**-0.442**	**0.014**	**LQLG$_{t}^{b}$**	**-0.448**	**0.013**
MQMG$_{t}^{b}$	-0.297	0.118	MQMG$_{t}^{b}$	-0.233	0.225
a: n=28; b: n=30					

Table 15: Co-Contraction and Strength 2 Years After TKA

Co-Contraction and Strength- Before TKA					
Knee Extensor Strength			Knee Flexor Strength		
	Spearman’s Rho	P- Value		Spearman’s Rho	P-Value
LQLH$_{wa}$	-0.271	0.276	LQLH$_{wa}$	-0.104	0.681
MQMH$_{wa}$	-0.036	0.887	MQMH$_{wa}$	0.226	0.367
LQLG$_{wa}$	-0.356	0.147	LQLG$_{wa}$	-0.216	0.390
MQMG$_{wa}$	-0.402	0.110	MQMG$_{wa}$	-0.203	0.434
LQLH$_{s}$	-0.484	0.042	LQLH$_{s}$	-0.368	0.132
MQMH$_{s}$	-0.063	0.804	MQMH$_{s}$	0.185	0.463
LQLG$_{s}$	**-0.519**	**0.027**	LQLG$_{s}$	-0.342	0.165
MQMG$_{s}$	**-0.583**	**0.014**	MQMG$_{s}$	-0.328	0.198
LQLH$_{t}$	-0.449	0.062	LQLH$_{t}$	-0.430	0.075
MQMH$_{t}$	-0.127	0.616	MQMH$_{t}$	-0.011	0.964
LQLG$_{t}$	-0.457	0.056	LQLG$_{t}$	-0.439	0.069
MQMG$_{t}$	**-0.598**	**0.011**	MQMG$_{t}$	-0.400	0.112
All n=18					

I then ran regression analyses with groups to determine how the relationship of co-contraction to patient function differs between stronger and weaker patients. I compared 6MW distance to LQLH co-contraction during the stance phase for two groups at each time point: strong patients and weak patients. At each time point, strong patients were defined as having normalized knee extensor strength above the mean for all patients at that time point. Before TKA, in both strong and weak patients, higher co-contraction was associated with worse performance on the 6MW (Figure 12). Six months after TKA, in strong patients, higher co-contraction was associated with worse performance on the 6MW (Figure 13). However, in weak patients, co-contraction was not associated with performance on the 6MW. Two years after TKA, in both strong and weak patients, higher co-contraction was associated with better performance on the 6MW (Figure 14). None of the relationships shown here are particularly strong.

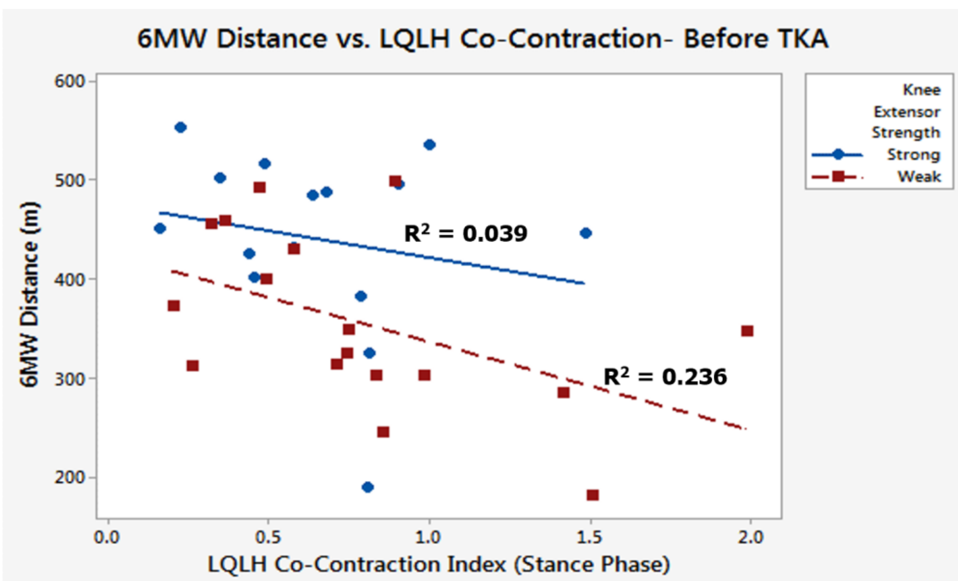

Figure 12: 6MW Distance and Co-Contraction for Strong and Weak Patients, Before TKA

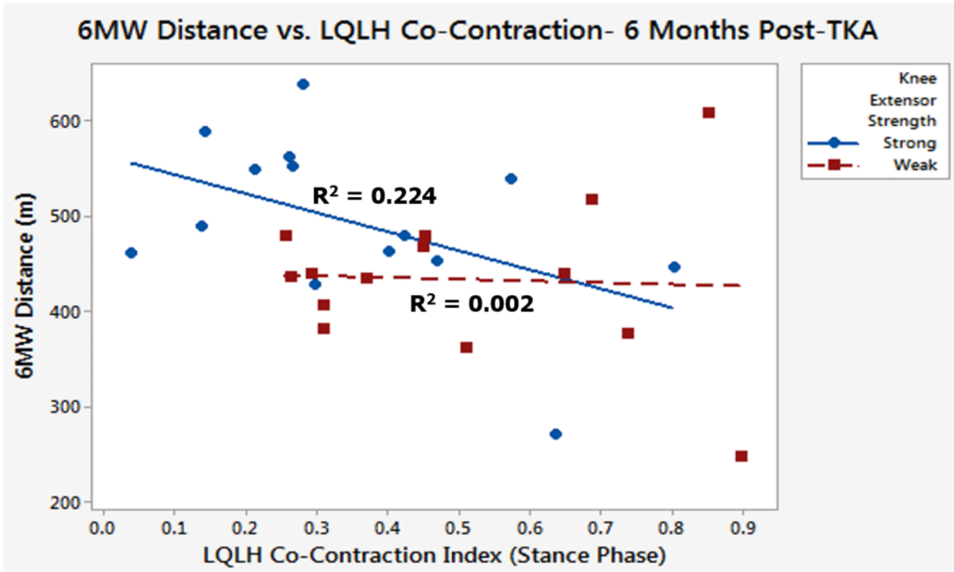

Figure 13: 6MW Distance and Co-Contraction for Strong and Weak Patients, 6 Months After TKA

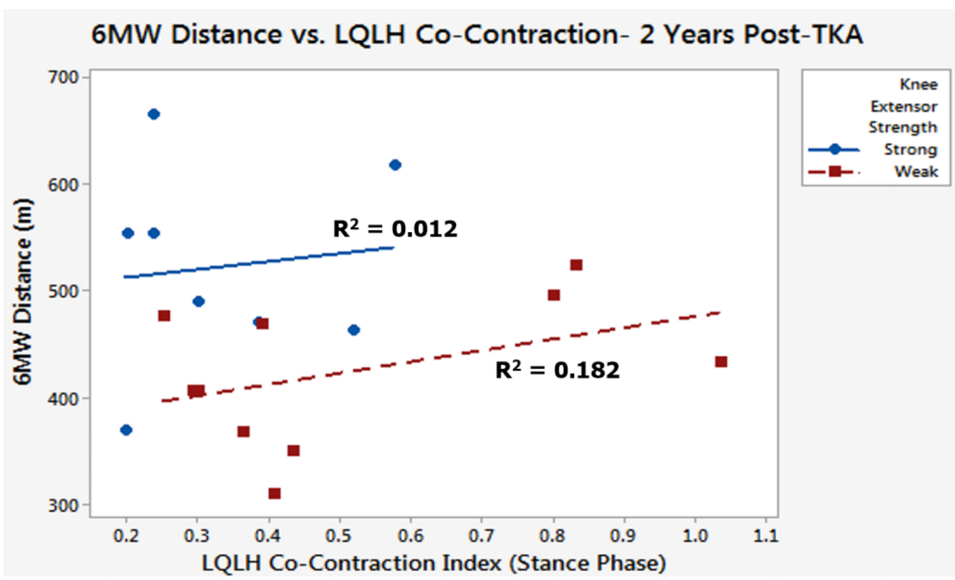

Figure 14: 6MW Distance and Co-Contraction for Strong and Weak Patients, 2 Years After TKA

Chapter 4: Discussion

4.1 Perceived Instability

Before surgery, perceived instability was related most strongly to knee strength. Greater instability was associated with weaker knee extensors and flexors. This suggests that before surgery, patient's perception of instability may be due to a lack of active stability provided by their knee muscles. Perceived instability is also weakly related to co-contraction before surgery. Only one co-contraction index (during both weight acceptance and stance) was associated with perceived instability, with higher co-contraction being associated with more perceived instability. Based on the relationship of co-contraction to strength found in section 3.3, it is likely that both co-contraction and perceived instability are responses to muscle weakness. Higher co-contraction may be used by patients to try to increase the active stability provided to their knee joint.

After surgery, perceived instability does not seem to be related to either co-contraction, strength, knee balance, or knee laxity. Six months after TKA, no relationships were statistically significant. Two years after TKA, only one co-contraction index was significantly associated with perceived instability, with higher co-contraction being associated with less perceived instability. At this time point, the correlation coefficients between co-contraction and perceived instability do not point to a clear association in either direction. From these data, I cannot conclude that perceived instability is associated with any of the measures I investigated after surgery.

4.2 Co-Contraction and Patient Function

The relationship of co-contraction to patient function differs depending on which phase of the gait cycle is considered. When comparing total gait cycle co-contraction to patient function, there is a weak association between higher co-contraction and worse function, both before and after surgery. However, this association is only statistically significant for a small number of co-contraction indices and measures of function.

Comparing co-contraction during the stance phase to patient function, higher co-contraction is weakly associated with worse function both before and six months after TKA. Two years after TKA, higher co-contraction is weakly associated with better function. Comparing co-contraction during the weight acceptance phase to patient function, higher co-contraction before surgery is weakly associated with worse function, and higher co-contraction after surgery is weakly associated with better function. Based on these results, it seems that the relationship of co-contraction to patient function changes two years after surgery. Initially I thought that this may have something to do with patients' pain. Increased pain has been related to worse function after TKA [30]. If co-contraction increases compressive forces in the joint, it could be increasing bone-on-bone contact. Before TKA, the presence of bone spurs and cartilage loss could mean that increased co-contraction causes pain and negatively affects function. Two years after TKA, when the joint has fully healed, increased compressive forces in the joint would only increase contact between prosthetic components, which would likely not cause pain, and thus not negatively affect function. However, this explanation is not supported by the data. Co-contraction was not related to pain as measured by the KOOS-Pain subscale.

For all phases of the gait cycle considered, co-contraction was more consistently related to 6MW performance than any other measure of function. I compared co-contraction indices between patients who performed better on the 6MW and those who performed more poorly, to see whether these groups of patients were utilizing different amounts of co-contraction. Before surgery, patients who performed better on the 6MW utilized significantly less co-contraction than patients who performed worse. After surgery, the relationship was not as strong. This could suggest that before surgery, co-contraction is a coping mechanism utilized by patients with worse function. After surgery, it is possible all patients, regardless of their levels of function, utilize the co-contraction strategy equally.

As a final test of whether co-contraction was related to better or worse function, I compared co-contraction during the weight acceptance phase to peak knee flexion angle. My reasoning was that if co-contraction was stiffening patients' knee joint and restricting their range-of-motion during gait, then co-contraction would be a detrimental strategy. I did not find that co-contraction was strongly related to peak knee flexion angle. Only one co-contraction index was significantly associated with peak knee flexion angle, with higher co-contraction actually being associated with a larger angle.

Based on these results, I cannot conclude that co-contraction is a detrimental strategy, or that it is significantly associated with worse function. Before surgery, patients with lower function may utilize the co-contraction strategy more than others, but this does not imply that co-contraction is related to worse function.

4.3 Co-Contraction and Knee Balance and Laxity

Co-contraction was not significantly related to knee laxity. In one case two years after surgery, higher co-contraction was significantly associated with greater knee laxity. However, this relationship is not strong enough to conclude that co-contraction is associated with passive knee laxity.

Before surgery, the relationship of co-contraction to native knee balance is unclear. Higher MQMG co-contraction during the weight acceptance phase and higher LQLG co-contraction during the stance phase were both associated with more valgus knee alignment. Six months after TKA, higher LQLH co-contraction was associated with valgus knee alignment. Although this relationship is not strong enough to draw any conclusions about how knee balance affects co-contraction, the results are still somewhat counterintuitive. If a patient has valgus knee alignment, the stabilizing ligaments on the medial side of the knee are less stiff than the stabilizing ligaments on the lateral side of the knee. It would make sense, then, that greater co-contraction on the medial side might be used to compensate for this. But, this relationship is not seen after surgery. It is also possible that if the patient's knee has a valgus alignment, the knee is constantly shifting or sliding to a more valgus position. In this case, the lateral stabilizing ligaments may experience a tensile force, causing them to stretch. The patient could compensate for this by utilizing greater lateral co-contraction.

4.4 Co-Contraction and Strength

The relationship between co-contraction and strength is the strongest I found in this research. Higher co-contraction was related to less knee muscle strength at all time points, but especially before and six months after TKA. This suggests that weaker patients utilize the co-contraction strategy because their muscles are not able to provide enough active stability without it.

Based on the measure of function and co-contraction index that I chose to investigate further, there are no major differences between how co-contraction relates to patient function in weak versus strong patients. The regression models do not reveal any strong trends.

4.5 Limitations

This research is limited by its observational nature. I can draw no conclusions about the causes of perceived instability or co-contraction. This research was also limited by the number of participants in the post-operative groups, and the quality of the EMG data. Due to missing or invalid data and loss of patients throughout the study, the statistical power of my analysis was limited in all groups, but especially in the post-TKA groups.

Conclusions

5.1 Contributions

This research is the first to investigate the relationship of perceived instability to co-contraction, and the relationship of perceived instability to strength and laxity after TKA. This research is also the first to investigate the relationship of co-contraction directly to performance-based and self-reported measures of patient function. While perceived instability after TKA was not related to any of the measures I studied, this research provides an important first step in uncovering why some patients continue to feel unstable after surgery.

5.2 Future Work

Future work should continue to investigate the effects of strength on perceived instability and co-contraction. In patients with OA before TKA, muscle weakness is strongly associated with a worse perception of instability. Interventional studies could be done to determine whether strength training programs can help alleviate OA patients' feelings of instability. Further research should also consider how strong and weak patients utilize the co-contraction strategy. It is possible that co-contraction affects function differently for weak and strong patients, but I only ran this analysis for one measure of function and one co-contraction index.

Future studies should also continue to investigate the relationship of knee balance to co-contraction. The size of this study limits the impact of its results. This field would benefit from a larger study investigating the effect of knee balance on co-contraction both before and after surgery.

5.3 Summary

This thesis investigated the relationship of perceived instability to co-contraction, strength, knee laxity, and knee balance. Before surgery, a greater perception of instability was associated with higher co-contraction and less strength. After surgery, perceived instability was not significantly associated with any of these variables. This thesis also investigated how the co-contraction strategy affects patient function, and what variables may affect co-contraction. Co-contraction was not significantly associated with patient function. Higher co-contraction is significantly associated with weaker knee extensor and flexor muscles.

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